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AN OPERANT APPROACH TO REHABILITATION MEDICINE: OVERCOMING LEARNED NONUSE BY SHAPING

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A new approach to the rehabilitation of movement, based primarily on the principles of operant conditioning, was derived from research with deafferented monkeys. The analysis suggests that a certain proportion of excess motor disability after certain types of injury involves a learned suppression of movement and may be termed learned nonuse. Learned nonuse can be overcome by changing the contingencies of reinforcement so that they strongly favor use of an affected upper extremity in the chronic postinjury situation. The techniques employed here involved 2 weeks of restricting movement of the opposite (unaffected) extremity and training of the affected limb. Initial work with humans has been with chronic stroke patients for whom the approach has yielded large improvements in motor ability and functional independence. We report here preliminary data suggesting that shaping with verbal feedback further enhances the motor recovery.

Key words: shaping, training, restriction, somatosensory deafferentation, stroke, rehabilitation medicine, impaired movement, monkeys, humans

This article describes a new approach to the rehabilitation of movement in physical medicine. It is based in its essential features on the principles of operant conditioning. It is fitting that it appear in a tribute to Joseph V. Brady, because he persuasively endorsed the relevance and importance of applying the principles of the experimental analysis of behavior to new areas and in this way strongly influenced the development of this work.

Experiments with Deafferented Monkeys

Although the present approach is fundamentally behavioral, the original observations were made in the context of studies of the neurophysiology of motor control and the role of sensory feedback in movement and learning. The spinal nerves, which are fundamental for these functions, emerge from the spinal cord in two roots. The dorsal root is sensory. Thus,

It is appropriate that this article appear in a tribute to Joseph V. Brady, because the basic approach that it represents stems from research carried out with monkeys given somatosensory deafferentation in a laboratory of the Institute for Behavioral Research (IBR) in Silver Spring, Maryland. Joe Brady was first a member of the Board of Directors of IBR and then Chairman of the Board. The animal rights group, People for the Ethical Treatment of Animals (PETA), tried to gain custodianship of the colony of deafferented monkeys; if they had succeeded, it would have set a dangerous legal precedent that would have had serious adverse effects on the future ability to conduct animal research in the United States. As Chairman of the IBR Board of Directors and, thus, the main representative of the owner of the monkeys, Joe Brady was subjected to an enormous amount of pressure to release the monkeys to PETA or agents that it designated. Some, but not all, of this pressure consisted of a petition demanding this action signed by a majority of the members of Congress, attempts at persuasion by direct contact by more than one half dozen members of Congress, attempts by NIH to convince him to accede to the political pressure, and the very negative reaction of his own university to his involvement in the situation. Nevertheless, Joe Brady, recognizing the importance of the case for the future integrity of the animal-research enterprise, responded by saying, to quote him, "They will get those monkeys over my dead body." As a result, the monkeys were preserved so that significant experiments could be carried out (Pons et al., 1991; Rausell, Cusick, Taub, & Jones, 1992). These experiments will not be described here because their subject matter is not directly relevant to the main theme of this paper, but there is widespread recognition of their potential practical importance for the fields of cortical plasticity and physical rehabilitation (Barinaga, 1992; Palca, 1991; Stephens, 1991). Thus, Joe Brady resisted pressure that very few could have withstood, and thereby achieved a significant victory for animal research on several levels. However, his role in this incident is largely unknown. He is an unsung hero. It is hoped that this account will help to some extent to begin to rectify this situation.

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by severing all of the dorsal roots innervating a limb, one can eliminate all sensation from that limb involved in the support of ongoing behavior sequences while leaving the motor innervation intact over the ventral root. In the monkey, when a single forelimb in a monkey is deafferented, the animal stops making use of it in the free situation (Knapp, Taub, & Berman, 1958; Lassek, 1953; Mott & Sherrington, 1895; Twitchell, 1954).

However, it was found to be possible to induce a monkey to use the deafferented limb by three general types of behavioral techniques. One type involved restriction of movement of the intact upper extremity through the use of a device that left the deafferented limb free (Knapp, Taub, & Berman, 1963; Stein & Carpenter, 1965). Use of the deafferented limb would usually begin within an hour of emplacing the restriction device, typically for postural support while the animal was in a sitting position. Within several hours, the limb could typically be used, although somewhat clumsily, for a wide variety of activities, including ambulation, climbing, and thumb–forefinger prehension of small objects.

When the restriction device was left in place for 1 or 2 days, removal of the device resulted in a remarkable reversion to nonuse of the deafferented limb. Even though the animals had used their limbs quite well for a wide variety of purposes when their intact arms were secured in the restriction device, the animals suddenly stopped using their deafferented extremities as soon as the device was removed and use of the intact limb was permitted. However, when the animals were left in the intact-limb restriction device for a longer period of time, as short as 3 days for 1 animal, the use of the deafferented limb persisted after the device was removed. There was no apparent diminution of range or quality of movement after device removal, and this level of use continued for the remainder of the animals' lives, which in one case was over 4 years (Taub, 1976, 1977, 1980).

A second behavioral method for overcoming the inability to use a single deafferented limb is the application of procedures for training use of that limb. In initial work, conditioned-response techniques were employed for enabling the animals to make a variety of movements with the deafferented limb, including phasic forelimb flexion (Knapp et al., 1958, 1963; Taub, Bacon, & Berman, 1965; Taub & Berman, 1963, 1968), grasp (Taub, Ellman, & Berman, 1966), forelimb flexion on a fixed-ratio schedule of reinforcement (Taub, Williams, Barro, & Steiner, 1978), sustained limb flexion (Taub, 1976, 1977), and compensation for progressively increasing loads on the arm (Taub, 1976, 1977; Wylie & Tyner, 1981, 1989). However, generalization to natural settings never occurred (Taub, 1976, 1977). The movements that were trained in the conditioning chamber were never observed in the colony environment. This lack of generalization was clearly similar to the results obtained by removal of the restriction device from the intact limb after insufficiently long periods of time.

A third, even more effective training method for inducing recovery of motor function was found to be shaping, in which a desired motor or behavioral objective is approached in small steps, by successive approximations (e.g., Morgan, 1974; Panyan, 1980; Risley & Baer, 1973; Skinner, 1938, 1968). With shaping techniques, the animals not only learned to employ a single deafferented limb in the training situation, but its use also generalized to the normal environment as well.

The actions shaped included (a) pointing at visual targets (Taub, Goldberg, & Taub, 1975) and (b) prehension in juveniles deafferented on day of birth (Taub, Perrella, & Barro, 1973) and prenatally (Taub, Perrella, Miller, & Barro, 1975) who had never exhibited any prehension previously. In both cases, shaping permitted an almost complete reversal of the motor disability, which progressed from total absence of the target behavior to very good (although not normal) performance.

Learned Nonuse and Overcoming Learned Nonuse

Substantial neurological injury usually leads to a shock-like phenomenon, whether at the level of the spinal cord (spinal shock) or brain (diaschisis or cortical shock). With regard to deafferentation, the elimination of somatosensory input results initially in a reduction in the background level of excitation within the spinal cord that maintains neurons in a subliminal state of readiness to respond. This effect is most marked in the deafferented segments of the spinal cord, where the depressed condition of motoneurons greatly elevates the threshold for incoming excitation necessary to produce movement. The early postsurgical spinal shock also may be partly due to active inhibitory processes. As time elapses following deafferentation, recovery processes, which are at present incompletely understood, raise the background level of excitability of motoneurons so that movements can once again, *at least potentially,* be expressed. The period of spinal shock lasts from 2 to 6 months in monkeys following forelimb deafferentation (Taub, 1977; Taub & Berman, 1968).

Several converging lines of evidence suggest that nonuse of a single deafferented limb is a learning phenomenon involving a conditioned suppression of movement (Taub, 1977, 1980). The restraint and training techniques appeared to be effective because they altered the contingencies of reinforcement, thereby enabling the learned nonuse to be successfully overcome. Thus, immediately after operation, the monkeys cannot use a deafferented limb; recovery from spinal shock requires considerable time. An animal with one deafferented limb tries to use that extremity in the immediate postoperative situation, but it cannot. Continued attempts to use the deafferented limb often lead to painful and otherwise aversive consequences such as incoordination and falling, as well as to loss of food objects, and, in general, to failure of any activity attempted with the deafferented limb. The resultant punishment leads to a conditioned suppression of attempts to use the limb. Moreover, the animal gets along quite well in the laboratory environment on three limbs; thus, these patterns of behavior are therefore positively reinforced and as a result are strengthened. The tendency not to use the deafferented extremity persists, and consequently the monkeys never learn that, several months after operation, the limb has become potentially useful.

When the movements of the intact limb are restricted several months after unilateral deafferentation, the contingencies of reinforcement are changed dramatically. The animal either uses the deafferented limb or it cannot with any degree of efficiency feed itself, move about, or carry out a large portion of its normal activities of daily life. This change in the contingencies of reinforcement "overcomes" the learned nonuse of the deafferented limb and induces the animal to use it. However, if the movement-restricting device is removed a short time after the early display of operant movement, the newly learned use of the deafferented limb acquires little strength and is, therefore, quickly overwhelmed by the well-learned tendency not to use the limb. If the movement-restriction device is left on for several days or longer, however, use of the deafferented limb acquires strength and is then able to compete successfully with the learned nonuse of that limb in the free situation. The learned nonuse formulation has received direct experimental support from two studies (Taub, 1977, 1980).

Shaping had several advantages over the conditioned-response training employed in our earlier work that enabled generalization of new use of the deafferented limb to the free situation: (a) There was the obvious advantage of a slow, step-wise procedure that could gradually lead an organism from a rudimentary initial response level to more complex responses. By allowing the extent of progress to determine the amount of time spent at each step, behavioral requirements did not exceed behavioral capacity excessively; thus, the likelihood of failure was reduced. (b) The responses being shaped more closely resembled those carried out in daily life in complexity and functional significance than did the type of simple and artificial movements adopted for convenience in the conditioning situations. (c) The shaping series took place over a much longer period of time and involved much more training than was the case in the conditioned-response situations.

Shaping stands partway between our earlier conditioned-response training and restricting movement of the intact limb, both conceptually and empirically, in its ability to enable generalization from the experimental intervention to the natural environment. Although shaping and intact-limb restriction represent two different approaches to the rehabilitation of movement, they are not mutually exclusive; indeed, from the outset they appeared to be potentially complementary. These two procedures were not employed jointly in the research with monkeys; however, it seemed reasonable to attempt this approach in the work with human stroke patients described below.

The mechanism of learned nonuse is depicted schematically in Figure 1, and the method by which techniques that overcome learned nonuse operate is presented in Figure 2. These models explain the motor phenomena that follow forelimb deafferentation in mon-

DEVELOPMENT OF LEARNED NONUSE

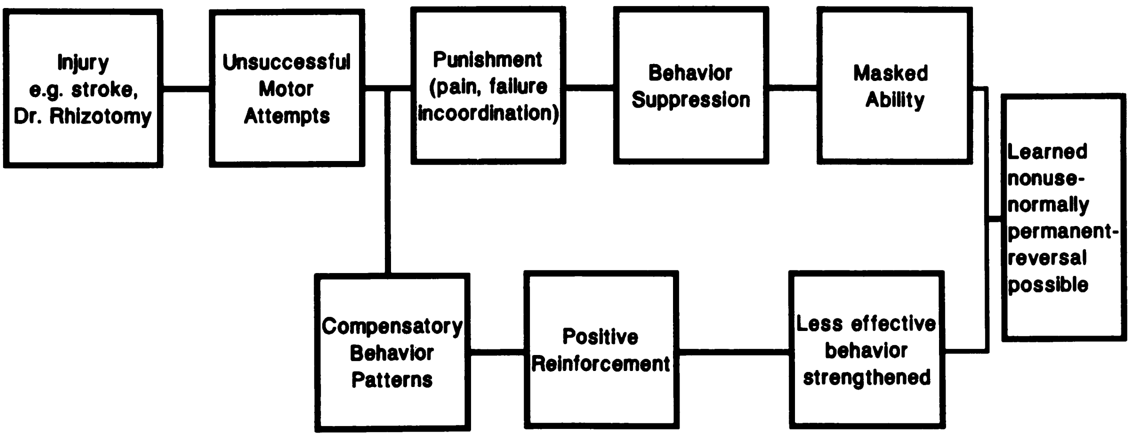

Fig. 1. Schematic model for development of learned nonuse. After Tries (1991).

keys. However, they are meant as more general formulations that also apply to other situations in which excess disability develops.

During the course of this century, several investigators have found that a behavioral technique could be employed in nonhuman animals to improve substantially a motor deficit resulting from neurological damage (Chambers, Konorski, Liu, Yu, & Anderson, 1972; Lashley, 1924; Ogden & Franz, 1917; Tower, 1940; Yu, 1980). There may thus be some interesting parallels in terms of the possible participation of a learned nonuse mechanism in the masking of the behavioral capacity actually present both after pyramidotomy and other motor lesions and after unilateral deafferentation.

Experiments with Human Patients After Stroke

Because the mechanism of learned nonuse is behavioral in nature, it was reasoned that it ought to be independent of the source and nature of an injury, coming into operation whenever the appropriate contingencies of reinforcement exist in the early postinjury period. For example, stroke in humans often leaves patients with an apparently permanent loss of function in an upper extremity, although the limb is not paralyzed. In addition, the motor deficit is almost always unilateral. These factors are similar to the situation that exists after unilateral forelimb deafferentation in monkeys. Therefore, it seemed reasonable to formulate a formal protocol for simply transferring the techniques used for converting a useless limb into one that could be used extensively from unilaterally deafferented monkeys to human patients after stroke (Taub, 1980).

Preliminary application of one of the conditioned-response paradigms developed in primate deafferentation research to human stroke patients had taken place previously with some success (Halberstam, Zaretsky, Brucker, & Guttman, 1971; Ince, 1969). Subsequently, Wolf and co-workers (Ostendorf & Wolf, 1981; Wolf, Lecraw, Barton, & Jann, 1989) took the limb-restriction portion of the published protocol (but not the training component) and applied it to chronic stroke and traumatic-brain-injury patients. The results were promising. They stimulated the next research effort (Taub et al., 1993), which made some modifications in the research design and added a training aspect (Taub, 1980) to the treatment of patients.

The subjects were chronic stroke patients who had experienced cerebrovascular accidents from 1 to 18 years earlier. Patients with this degree of chronicity, according to the traditional belief of the field, have presumably reached a plateau in their motor recovery and

OVERCOMING LEARNED NONUSE

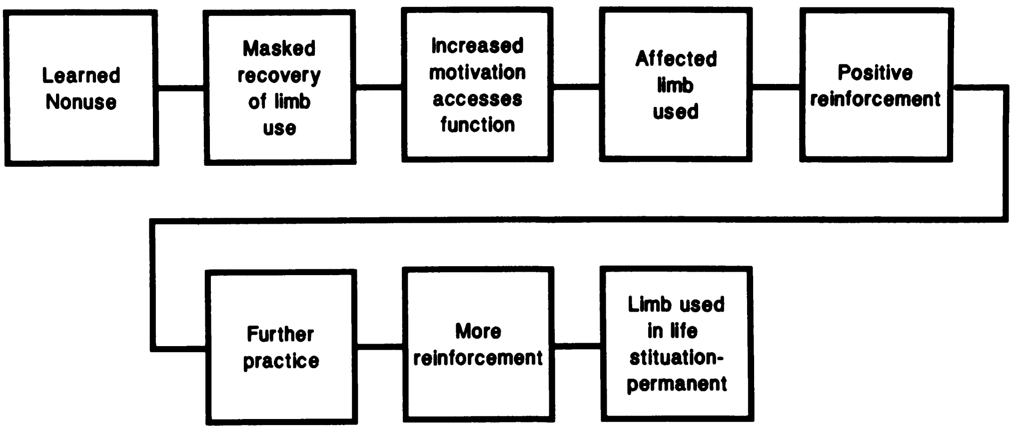

Fig. 2. Schematic model of mechanism for overcoming learned nonuse.

will not exhibit any further improvement for the rest of their lives. The focal criterion for inclusion in the study was the ability to extend at least 20° at the wrist and 10° at the fingers.

Nine persons who met the study's inclusion criteria (Taub et al., 1993) were assigned by a random process to either an experimental group (4 subjects) or to an attention-comparison group (5 subjects). The subjects in the two groups were closely matched in initial motor ability and did not diverge significantly in major demographic characteristics or in chronicity (median 4.1 years for the restraint group; median 4.5 years for the comparison group).

For the experimental group, the unaffected limb was secured in a resting hand splint and was then placed in a sling; the affected arm was left free. The restraint was to be worn at all times during waking hours except when specific activities were being carried out (e.g., excretory functions, naps, and situations in which balance might be compromised). A behavioral contract was drawn up for each subject, and in each case he or she agreed to spend approximately 90% of waking hours in restraint. The restraint devices were worn for 12 days. On each of the 8 weekdays during this period, patients spent 7 hr at the rehabilitation center and were given a variety of tasks to be carried out by the paretic upper extremity for 6 hr (e.g., eating lunch with a fork and spoon; throwing a ball; playing dominoes, Chinese checkers, or card games; writing on paper or on a chalk board; pushing a broom; using the Purdue Dexterity Board; taking the Minnesota Rate of Manipulation Test). No explicit training of any kind, including shaping, was given; the subjects simply practiced the tasks repeatedly. The purpose was primarily to provide experience and overtraining in use of the affected limb.

The procedures given to the comparison group were designed to focus attention on the involved extremity. This was accomplished in three ways. First, patients were told (during four periods on separate days) that they had much greater motor ability with their affected extremity than they were exhibiting; they were exhorted to focus attention at home on using the affected extremity in as many new activities as possible. Examples were given, and record keeping was required and monitored. Second, patients received two sessions (labeled physical therapy) that involved only those activities that required neither active movement nor limbering of the involved limb. Third, patients were given self-range-of-movement exercises to carry out at home for 15 min a day. In these exercises, the affected extremity was passively moved into a variety of positions by the unaffected extremity.

Two laboratory tests of motor function were administered to experimental and comparison subjects just before and immediately after their 2-week intervention period. One test consisted of simple limb movements, half without functional end points (Wolf et al., 1989). The other was composed of more complex tasks involving complete activities of daily living (McCulloch et al., 1988). To summarize the findings of Taub et al. (1993), there were significant changes in the motor ability of the subjects whose uninvolved extremity was restricted, and these changes were large. The mean performance time of the experimental subjects decreased 38% on the first test and 28% on the second. The subjects also exhibited substantial increases in measures of quality of movement and functional ability in the two tests. There were particularly large improvements on the two tasks that assessed strength. In the 1 experimental subject given specific strength training, ability to lift weights by flexion at the shoulder increased 808.9%, and grip strength increased 275%. In contrast, the performance of the comparison group was not significantly changed at their postintervention testing on any of these parameters.

A third instrument, the Motor Activity Log (MAL), provided information about motor function in the normal environment, thus addressing the critical issue of generalization. This log consists of ratings of 14 common and important activities of daily life from such functional areas as feeding, dressing, and grooming. The comparison subjects did not improve on this scale in relation to the year preceding their entry into the project. In contrast, the movement-restriction subjects improved almost 2.5 rating steps (out of 6). There was virtually no overlap in the records of the two groups during treatment or during the follow-up period. Moreover, the treatment gains of the experimental subjects were fully maintained 2 years after the completion of the 2 weeks of treatment.

The improvement of the movement-restriction patients in MAL scores in part reflects better quality of movement and in part reflects the fact that these patients were able to translate the improvements made in the laboratory into mastery of a large range of daily activities that they had not previously been able to carry out with the affected arm. The new activities included brushing teeth, combing hair, picking up a glass of water and drinking, eating with a fork or spoon, and writing, among others. There was a mean increase of 97.1% in the number of activities on the MAL that the patients reported they could carry out 1 month after restraint compared to the period before treatment. The comparable change for the comparison subjects was 14.5%. The difference between groups on this measure was statistically significant after the interventions (U test, $p < .01$) but not before.

In interviews, each of the restraint patients stated that they were capable of a greatly expanded range of activities. They reported that they had made major gains in what was, in effect, functional independence. This is consistent with the results from the MAL. In the most dramatic case, motor improvement was great enough to permit part-time clerical employment. One of this subject's main tasks was answering the phone with the unaffected hand and writing messages with the affected hand. She was thus able to relieve a self-reported depressed state because she previously "had nothing to do except spend most of my days staring at the four walls of my apartment."

Shaping As a Means of Facilitating Overcoming Learned Nonuse in Human Chronic Stroke Patients

In monkeys, restriction of the intact limb and shaping had been used independently to improve motor function after unilateral forelimb deafferentation. With human chronic stroke patients, unaffected limb restriction had been combined with practice of use of the affected limb, but no explicit training of limb movement had been given. It seemed reasonable to combine shaping with limb restriction as complementary and possibly synergistic techniques for overcoming learned nonuse. This approach is being carried out in current work.

A battery of approximately 30 tasks was developed with a preliminary shaping plan for each. The actual subset of tasks selected for use with each subject depended on (a) specific joint movements that exhibited the most pronounced deficit, (b) the joint movements that staff members felt had the greatest potential for improvement, and (c) subject preference among tasks that had similar potential for producing specific improvements. The three tasks

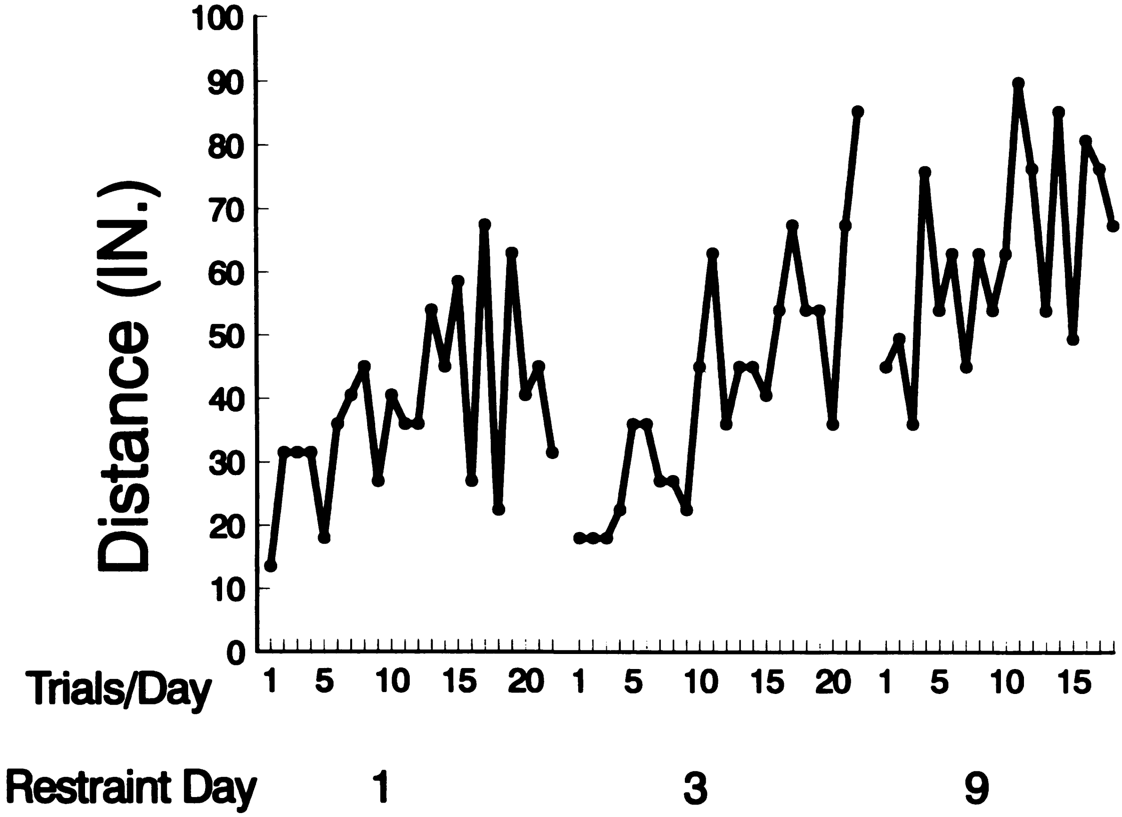

Fig. 3. Shuffleboard task. Distance disk moved over trials. Data are from three consecutive shaping sessions in which an attempt was made to increase the distance that a shuffleboard disk could be cast by a pole held by the affected upper extremity of a chronic stroke patient. Sessions occurred on Days 1, 3, and 9 of restraint of the unaffected limb.

described here are those for which data are provided in Figures 3 through 5. Other tasks are listed below to provide the reader with a general idea of the nature of the training program.

Shuffleboard. This task involved casting a shuffleboard disk with a pole as far as possible along a court from a standard starting position and a standard standing posture. The parameters shaped were (a) distance from start line to the leading edge of the disk and (b) the quality of movement rated on a 5-point scale employed in a previous study with stroke patients (Taub et al., 1993, in which the criteria for each step are explicitly defined). This task tended to be favored by subjects, presumably because of its recreational associations and because it provided direct and immediate feedback as to performance relative to previous attempts. The main joints involved were shoulder and elbow. The left edge of the court was demarcated at 22.9-cm intervals with distance-labeled horizontal strips of red plastic tape to give subjects immediate information about the distance of each cast. The leading edge of the disk on the farthest cast of a current session and the farthest cast of each previous session for that subject were indicated by strips of red tape placed in the middle of the lane, thus providing a continuous indication of the nature of the present behavioral requirement.

Rotation of Rolodex® file. A Rolodex® file (12.7 cm diameter) had to be rotated by a seated subject by turning one of two knobs (5.7 cm diameter) protruding from the center of either side of the file. The movement required was grasp (of the knob) and ulnar deviation and some flexion of the wrist. The arm of the subject was unsupported and had to be kept in flexion at shoulder and elbow. All joints of

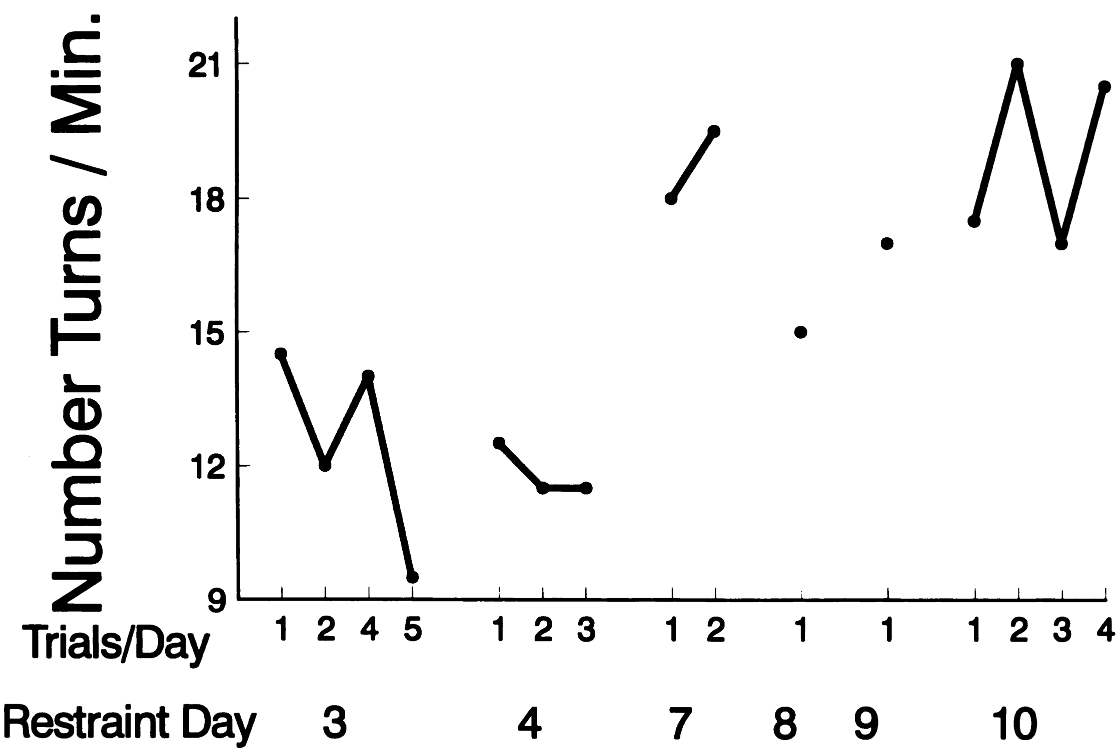

Fig. 4. Rolodex® task. Data are from consecutive shaping sessions involving an attempt to increase the number of rotations per 1-min trial of a knob that turned a circular card file.

the arm were involved in the activity. A thin piece of red tape secured across the radius of the knob was continued (with an interruption) onto the frame of the file. A trial began with the segments of tape on the knob and frame lined up; the completion of one rotation was indicated when the two segments were again lined up. The experimenter informed the subject of performance progress by counting complete rotations out loud. The parameters shaped were (a) number of rotations per minute and (b) quality of movement. Although the limiting factor in performance tended to be the ability to make the appropriate movements at the wrist, difficulty frequently was encountered in keeping the arm maintained in shoulder flexion for a period of 1 min.

Moving a ball. The hand of a seated subject grasped the soft top of an inflatable plastic ball (20.3 cm diameter) placed on a table surface directly in front of the subject at a distance that required the arm to be fully extended. Talcum powder was spread lightly on the table surface to decrease friction. One subtask required the subject to slide the ball from side to side with the arm fully extended at the elbow from one edge of a table (1.2 m diameter) to the other for four repetitions of both movements. Subtask 2 involved grasping the ball with the arm in full pronation (palm down), fully extended at the elbow and in approximately 70° flexion at the shoulder, and then rotating the ball back and forth four times by moving into 30° to 40° supination, returning to full pronation and then moving the ball in the opposite direction by internally rotating the shoulder till the fifth digit was uppermost on the ball. Subtask 3 required the subject to slide the ball backward till the arm was in 90° flexion at the elbow and then forward to the original fully extended position. The parameters shaped were (a) time to accomplish the four cycles of movement, (b) amount of supination and internal rotation at the shoulder (for Subtask 3), and (c) quality of movement. The three subtasks were sometimes carried out in the same session and sometimes in separate sessions. They involved activity at all joints.

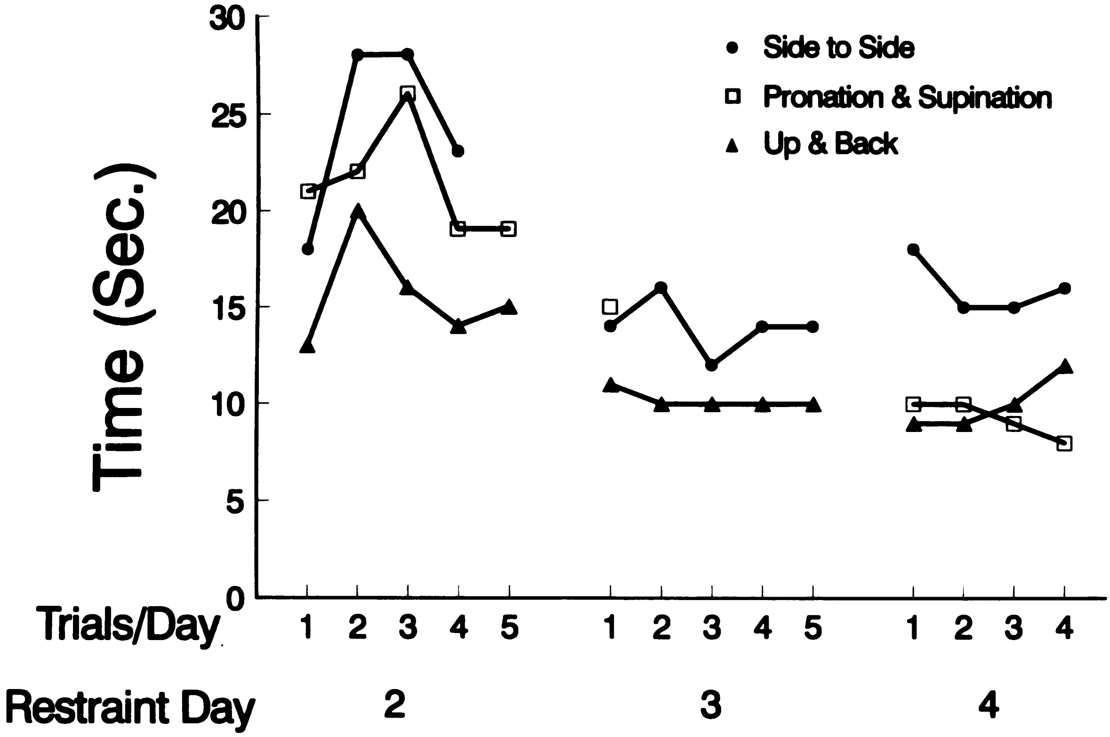

Fig. 5. Rolling ball task. Data are from consecutive shaping sessions for three subtasks involving movement of an 8-in. (20.3-cm) diameter ball on a table in front of the seated subject: (1) sliding ball from side to side, (2) rotating ball by supinating and internally rotating arm, and (3) sliding ball toward and away from the torso. The *y* axis displays the time(s) to perform eight side-to-side movements, four pronation/supination movements, or four backward/forward movements.

Additional tasks included tap telegraph key, place ring on a prong in front of the subject, place ring on a prong above the subject, trace circles, shave (simulated), pat powder puff on face, brush teeth (simulated), dot-to-dot drawing, use children's building blocks to create a tower, place graduated weights on different height boxes, write signature, and use spoon or fork with simulated pieces of food.

General considerations. All training is carried out with movement of the unimpaired upper extremity restricted by a resting hand splint and sling. At the beginning of work with a subject, new tasks are often designed that are tailored to provide training for the movements that are weakest in that individual. Each task must have aspects that are easily quantifiable, preferably so that small improvements are immediately apparent to the subject. Rest intervals are introduced in each shaping session. The rest periods are usually the same length as the trial periods, though longer intervals are sometimes used to prevent fatigue. Verbal reinforcement is given enthusiastically after the smallest performance improvements are detectable. The experimenter's verbal response is intended to provide detailed information in terms of the specific nature of the improvement. In addition, maintenance of previous gains is acknowledged on each occasion. Performance regressions are never punished and are usually ignored. When performance has not increased for approximately three trials, the subject is encouraged to improve further (e.g., "Let's see whether we can go a little further on the next try"). Liberal use is made of modeling and prompts. At the beginning of a shaping series, subjects may be given physical help in carrying out parts of a movement sequence they cannot do themselves. In physical therapy, this is termed "assisted movement." This aid is attenuated and then faded as soon as is feasible. If a subject is having too much trouble making progress in a task, a simpler task involving similar movements is substituted.

Preliminary results. Figures 3 through 5 present the trial-by-trial data for 1 subject for the first three tasks described above. He was the first individual given restriction of unaffected limb movement (12 days) while receiving training of the affected limb by shaping procedures (8 days). In the shuffleboard task, the distance the disk was cast increased progressively over the three shaping sessions (Figure 3). A trend analysis revealed a statistically significant linear improvement across days, $t(60) = 4.98, p < .0002$. The mean cast during the first shaping session was 98.6 cm, and in the third training session it had increased to 159.5 cm. The first cast in the first session was 34.3 cm, whereas the peak cast in the third session was 228.6 cm. There was also a clear upward trend across trials within sessions.

In the Rolodex® task (Figure 4), mean number of circular file rotations per minute increased from 12.5 in the first shaping session to 19.0 in the last (sixth) shaping session. The linear change across days was statistically significant, $t(13) = 4.48$, $p < .0007$.

The data for the task involving moving the ball are presented in Figure 5. Subtask 1 involved eight movements of sliding the ball from side to side. There was a statistically significant linear decrease over days in the amount of time required to accomplish this task, $t(14) = -2.73$, $p < .003$. The mean time to make the eight movements was 24.4 s in the first session, and in Session 3 it was 16.1 s. In Subtask 2, four cycles of rotation of the ball from full pronation of the arm, first by supination and then by internal rotation of the shoulder, required a mean time of 27.3 s in the first session but only 9.2 s by the third session. The linear change across days was statistically significant, $t(7) = -7.82$, $p < .0001$. For Subtask 3, the mean time to complete four forward and four backward sliding movements of the ball decreased from 15.6 s in Session 1 to 10.3 s in Session 3. The linear improvement across days was again statistically significant, $t(12) = -3.82$, $p < .003$.

A series of training sessions was carried out with this subject for 11 other tasks involving 58 parameters that were either shaped or simply quantified over time. Trend analysis indicated that significant improvement occurred for 39 of these parameters, there was a trend ($p < .10$) toward improvement on two, and improvement did not occur for 17. At least one parameter improved on each task (except for the one involving drawing circles within printed boundaries).

The improvement recorded in motor performance on the tasks for which shaping was carried out is of interest, but it would have only technical relevance unless it generalized to other situations, both in the laboratory (where it could be measured objectively) and especially in the normal environment. Therefore, it is encouraging that in both cases very substantial motor improvement was recorded. On the Emory Motor Function Test (Wolf et al., 1989), mean performance time was 2.3 times as fast at the end of treatment as before treatment, going from a mean of 9.3 s per test item to 4.0 s. The increase in speed occurred on each of the 15 timed tasks; a sign test indicated that this increase was statistically significant at the .0003 level. The improvement in performance time was greater than for any previous subject given an intervention for overcoming learned nonuse; the mean increase in speed of previous subjects was 1.6 times (range, 1.3 to 1.8 times). Ratings of movements made during administration of the Emory Test indicated that performance on both Functional Ability and Quality of Movement Scales (Taub et al., 1993) improved significantly from pretreatment to posttreatment (ps $< .003$). The Emory Test includes two tasks that assess strength. Grip strength, as measured by a dynamometer, increased 1.7 times. This represents considerably greater improvement in grip strength than had been observed in any previous subject not given specific strength training (range, 0.9 to 1.2 times). A second task involved lifting progressively increasing weights strapped to the forearm from the surface of a table to the top of a box (22.9 cm). Before intervention, the maximum weight that could be lifted was 5 kg. After intervention, this level was exceeded easily, and additional weights were added incrementally until the subject reached his maximum at 13.6 kg, an increase of 2.8 times compared to pretreatment.

This subject's mean Motor Activity Log rating across tasks went from 2.2 for the week before treatment (2.0 = slight use) to 3.6 at the end of treatment (moderate to almost normal use). At 8 weeks after the end of treatment (the last scheduled follow-up point before the date of this writing), the score remained at virtually the same level of improvement (3.7). Paired *t* tests revealed that the improvement from baseline values was statistically significant from the 5th day of treatment until the 8th week of follow-up (*p*s from .006 to .0001). A parallel rating form completed by the subject's wife confirmed that improvement in functional ability had occurred. Her ratings increased, although not quite as much as her spouse's, from 2.1 (slight use) at pretreatment to 3.1 (moderate use) 1 week after the end of treatment.

At the time of this writing, 2 additional chronic stroke patients have just completed treatment for overcoming learned nonuse under shaping protocols. The data have not yet been analyzed, but inspection indicates that the results for these subjects are somewhat better than for the 1st subject. For the 2nd subject, for example, mean MAL score went from 0.8 pretreatment to 3.0 posttreatment, and for the 3rd subject, mean MAL score increased from 0.3 (0 = no use) to 3.1 for the same period. These ratings were confirmed by the independent scores of significant others on collateral forms. The 1st subject was not given a posttreatment home practice program and, as noted, his MAL score did not improve substantially during follow-up. In contrast, the second 2 subjects were given home practice programs and reported using them. The 2nd subject improved from 3.0 at the end of treatment to 3.9 and 3.4 at the 1st and 2nd weeks of follow-up, respectively. The 3rd subject's scores increased from 3.1 at the end of treatment to 4.3 (4.0 = almost normal) at the end of the 3rd follow-up week when he reported driving a car using both hands to steer and sharing cooking duties with his wife.

The new data reported here are from the first 3 subjects given shaping as part of the effort to overcome learned nonuse. These preliminary results are promising, and suggest that behavioral shaping improves the therapeutic outcome. However, data from additional subjects given similar treatment are needed before conclusions can be drawn concerning the quantitative role of shaping in the recovery of motor function.

During the 2nd week of shaping, the 2nd subject repeated with wonder several times a day some variant of the following quote, "I guess I stopped trying to use my left [affected] arm. I just didn't realize it." On an experiential level, this is an excellent encapsulation of the phenomenon of learned nonuse. We have had similar reactions from most of our previous subjects.

General Summary

Supervised practice of the use of an impaired upper extremity (but not shaping), in combination with restriction of an unimpaired limb, greatly increased the motor improvement that occurred in stroke patients compared to the improvement observed when only the motor restriction portion of the overcoming-learned-nonuse protocol was employed (Wolf et al., 1989). The data reported here from 3 subjects suggest that by substituting shaping for uninstructed task practice, motor improvement can be improved still further. Because shaping is simply a technique for improving the efficiency of certain types of training, it is conceptually reasonable that this should be the case. However, the data are at present limited, and firm conclusions are therefore not yet warranted.

The analysis given earlier in this article suggests that the development of learned nonuse is based upon the operation of the contingencies of reinforcement that are in effect following an injury that produces an initial motor deficit. It follows that the development of learned nonuse should not be confined only to cases of somatosensory deafferentation in monkeys and stroke in humans, but should occur in some proportion of individuals after many different types of injury. The operation of this mechanism would be disabling if there was a subsequent slow recovery or healing whose potential motor effects were masked by the learned nonuse. As noted above, the mechanism is behavioral and, as such, should be relatively independent of the locus of the injury. Therefore, it is proposed that learned nonuse is a factor in the development of some excess motor disability. (For a more complete discussion see Taub, 1994.) This is a widespread clinical phenomenon that occurs in connection with a number of conditions (Taub, 1980), especially in the aged; it is characterized by a motor deficit that is greater than appears to be warranted by the organic status of the individual.

Strokes almost always involve unilateral upper extremity motor deficits. Restricting the movement of the unimpaired upper extremity in these cases is an obvious procedure to help overcome the learned suppression of movement underlying learned nonuse. However, when the motor deficit is bilateral or involves the lower extremities, constraint of function may often not be as simply applied as restriction of an unimpaired arm. Thus, in bilateral and lower extremity conditions, shaping may assume even greater importance as a means of overcoming learned nonuse than following stroke.

In our laboratory, stroke patients are selected for study on the basis of whether they have more than a minimum ability to extend the wrist (20°) and fingers (10°), but who make little use of the affected extremity. This includes 20% to 25% of the chronic stroke population with motor deficit (Wolf & Binder-Macloud, 1983). To date, every one of the 7 subjects who have met this criterion have exhibited large improvements in the use of the affected limb in the normal environment when given treatment for overcoming learned nonuse. The percentage of stroke patients who do not meet this criterion, but who would also benefit from this therapeutic approach, is at present unknown. It would presumably not be as high as in the current work, but at least some of these patients might also be helped. Following stroke and traumatic brain injury, overcoming learned nonuse has been used with success in clinical situations (Desai, 1991; Tries, 1989, 1991; N. Birbaumer, personal communication, 1993; S. L. Wolf, personal communication, 1993).

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